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Cutting of Structural Materials Utilizing High Powered CO2 Laser

No. 8A-2

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ABSTRACT

The method most commonly used for cutting thick 1.90 cm (.75 inch) steel material where edge quality is not of a concern is flame cutting which utilizes an oxyacetylene torch. It provides the energy to heat the steel beyond its melting point and gas pressure forces the molten material (dross) through the thickness of the material. Cutting torches typically remove a kerf of approximately .63 cm (.25 inch) to 1.27 cm (.5 inch). Gas cutting is noisy, generates large quantities of smoke into the environment and forms large pieces of dross which can travel up to 3.04m (10 ft) and cause fires. Typically, when flame cutting shipboard, a fire watch is required. Also, if any type of flammable material exists on the opposite side of the cut, it must be removed for several inches on both sides of the cut line to preclude backside combustion. A search for a better method of cutting thick steel sections. including those with coating materials attached, centered around a high powered CO_2 laser. The CO_2 laser had successfully demonstrated its ability to weld heavy sections of steel with 100% penetration from one side and create a very narrow heat affected zone (HAZ). It was decided to expand this welding process to cutting by introducing high pressure assist gases. The gas would force the molten puddle created by the focused lsoer beam. through the steel material, thereby, creating a cut through the material as opposed to allowing the molten material to fuse back together without the assist gases (creating a welded Joint). It was decided to take advantage of the laser's high powered density to cut/vaporize non-metallic material attached to the steel plate. Also, there was interest in the effects of a laser beam on asbestos material.

LIST OF ACRONYMS

MPa	Mega Pascals
HAZ	Heat Affected Zone
ARL	Applied Research Lab
ICP	Inductively Coupled Plasma Spectrometry
PCB	Polychlorinated Biphenyl
HY	High Yield
HTS	High Tensile Steel
0^2	Oxygen
N_2	Nitrogen
CPM	Centimeter Per Minute
CPS	Centimeter Per Second
CUNI	Copper Nickel
ft	foot
UTIL	United Technologies Industrial Lasers
YAG	Yttrium Aluminum Garnet
mm	millimeter
cm	centimeter
m	meter
in^5	square inch

INTRODUCTION

In order to determine the cutting feasibility of a high powered CO_2 laser through thick steel and non-metallic coatings, a test program was developed to collect data. Mare Island Naval shipyard had been the designated laser welding center of excellence for the Navy. Practical experience existed there for the laser applications. Under funding from the program sponsor, Naval Sea Systems Command, the shipyard entered into a contract with the Applied Research Lab (ARL). Pennsylvania State University which previously performed laser materials processing developing with lasers from 400 watts to 25 Kw. The combined effort also included United Technologies Industrial Lasers (UTIL) who had expertise in gas nozzle design and manufacture of high power (greater than 6 Kw) CO_2 lasers. The test program was to evaluate laser cutting parameters such as travel speed. power range. nozzle configurations, gas pressure and gas composition. The cutting was performed inside a chamber so that environmental data could be collected and analyzed. Also. there was interest In temperature gradients at various distances from the cut area. The shipyard was to provide both coated and uncoated material samples of various compositions and thicknesses.

TEST PROGRAM

Test Samples

The shipyard manufactured a series of 30.48 cm (1 ft) by 60.96 cm (2 ft) sample flat plates for testing of various thicknesses and materials as follows.

1. 30.48 cm (12 inches) x 60.96 cm (24 inches) x 1.0 cm (.375 inch) thick HTS Plate (MIL-S-22698 Grade DH) with rubber sound damping on both sides, final painted with approximately .30 mm (12 mils) of epoxy paint. Figure 1 denotes the thickness of the layered materials.

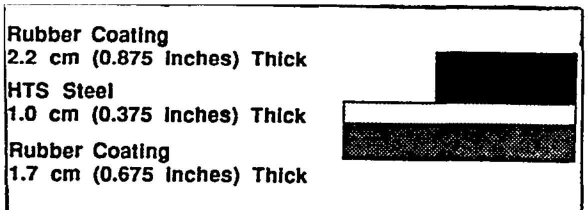

Fig. 1 Material Test Sample

2. 30.48 (12 inches) x 60.96 cm (24 inches) x 3.2 cm (1.25 inches) thick HY-80 plate (MIL-S-16216) with rubber sound damping on one side, foam insulation on opposite side and painted with approximately .30 mm (12 mils) of epoxy paint. Figure 2 denotes the thickness of the layered materials.

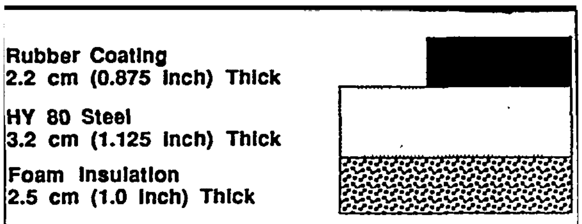

Fig. 2 Material Test Sample

3. 30.48 (12 inches) x 60.96 cm (24 inches) x 5.1 cm (2 inches) thick HY-80 plate (MIL-S-16216) with rubber sound damping on one side, foam insulation on opposite and painted with approximately .30 mm (12 mils) of epoxy paint. Figure 3 denotes the thickness of the layered materials.

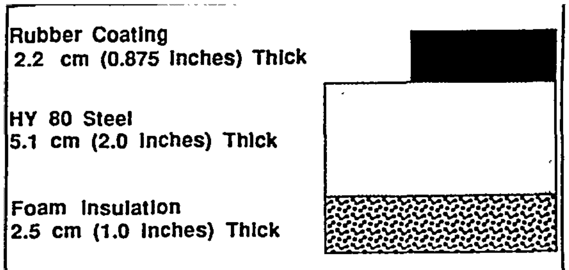

Fig. 3 Material Test Sample

Other HY-80 steel samples for parameter testing were provided in thicknesses from 1.90 cm (.75 inch) to 5.40 cm (2.12 inches). In addition, a 5.08 cm (2 inches) diameter pipe sample coated with 5.08 cm (2 inches) of asbestos was provided and a 6.35 cm (2.50 inches) diameter section of shielded 400 ampere power cable.

Laser Selection

The original development work for the CO_2 laser welding was performed at the ARL Penn State's Research Facility utilizing a 14 Kw CO_2 laser. Laser processing, developed at ARL has been transferred for Navy and private application to Stardyne, Inc., a high powered laser job shop in Johnstown, Pennsylvania. It was in Johnstown where the actual laser cutting testing took place. The CO_2 laser development work centered around the successful welding of medium to heavy steel plate sections. It was this existing welding technology coupled with the inherent ability of the CO_2 laser to produce constant high power 10^{10} watts/cm^3 (10^{Y} w watts/in^3) over long periods of time that provided the basis for its selection for this program. It also provided an off-the-shelf power unit capable of making the transition from the lab to field application in shipyards and other industrial facilities.

Testing Work Station

The actual testing was accomplished at a work station approximately 45.72 m (150 feet) from the 25 Kw Co_2 laser location. The laser had eight mirrors from the power source through the various bends in its 45.72 m (150 feet) transmitting tube to the work station. The power loss from the laser's aero-dynamic window to the work station was approximately 12% (1.5% at each mirror). The power levels quoted in this report are the power levels at the laser source. The work station was a 10.97m (36 feet) long sidebeam gantry with focusing optics mounted on the sidebeam carriage. The carriage had a top speed of 4.23 cps (100 inches/minute). A cutting chamber was mounted directly under the laser focus head. The cutting chamber was stationary and supported the sample to be cut. It also featured a sliding cover which moved with the laser beam over the surface area to be cut. The chamber also had a viewing port and exhaust duct to collect environmental samples. The laser focusing optics had a focal length of 44.45 cm (17.5 inches) (F Number=7.6). The laser beam entered the optics box with approximately 7.62 cm (3 inches) diameter coherent light beam and was then focused down to a spot size of .13 cm (.050 inches) in diameter (Figures 4, 5A & 5B).

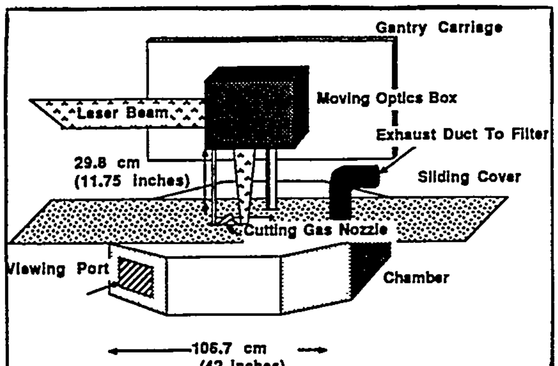

Fig. 4 Diagram of Cutting Chamber Arrangement

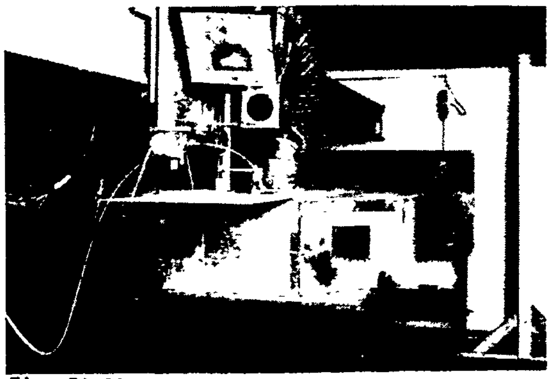

Fig. 5A Side View of Cutting Chamber

Fig. 5B End View of Cutting Chamber

Cutting Nozzles

Three stainless steel hypo tube nozzles were used, 51 mm (.020 Inch), 1.14 mm (.045 inch), and 1.57 mm (.062 inches) in diameter. The nozzle used for most of the testing was a 1.57 mm (.062 inch) diameter hypo tube. The tube was orientated 25 degrees from the vertical axis and positioned to aim the high pressure assist gas at the laser beam Interaction/focus point. (Figure 6 and Figure 7).

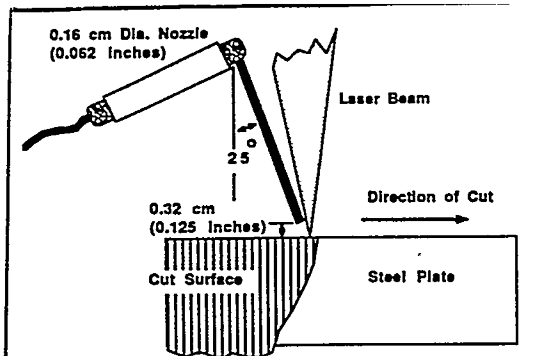

Fig. 6 Cutting Nozzle Orientation with Respect to Laser Beam Interaction Point

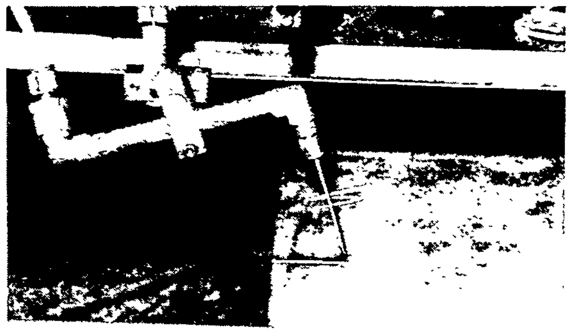

Fig. 7 Side View of Cutting Gas Nozzle

High Pressure Assist Gases

With the 25 Kw available energy source, sufficient power was available to accomplish cuts through thick sections. The next most important consideration affecting laser cutting is the gas jet nozzle design and the type and pressure of assist gases. For this cutting program, three types of assist gases were tried separately, pure oxygen (O_2), air, and nitrogen (N_2). Oxygen might directly contribute to oxidation and cutting speed, yet, in other applications where the flammability of backside materials was of primary concern, an inert assist gas such as N_2 might prove more valuable. The gases were stored in standard 'K' size cylinders and were regulated to a maximum pressure of 5.50 MPa (800 psig). A hose connected the cylinders to the gas nozzle via the regulator.

Environmental Procedure

The shipyard environmental

technicians collected airborne samples from selected cuts both inside and outside the chamber utilizing 2.54 cm (1 inch) diameter cassettes and low volume pumps. A syringe was also used to collect air samples inside the chamber. In addition, the exhaust gases from the chamber were collected via a 283 liters/sec (600 cubic foot per minute) pump. across a .3 Micron (.0012 inches) HEPA filter. The filter was changed during the cutting process and weighed before and after its use to determine the amount of material trapped. The filters were then sent to an independent laboratory to determine the existence amount of a possible 24 elements trapped in the filters. The method used for analysis was inductively coupled plasma (ICP) spectrometry.

Thermocouple Procedure

The temperature gradient generated by the CO_2 laser in the material during the cutting operation was of extreme interest. This was especially true for critical heat zones for a future test program involving laser cutting through steel layered with polychlorinated biphenyl (PCB) impregnated materials. Accordingly, thermocouples were mounted on the top surface (same side as laser beam) of selected steel plates in .63 cm (.25 inch) increments to a distance of 2.54 cm (1 inch) from the centerline of the laser cut (i.e..., .63 cm (.25 inch), 1.27 cm (.50 inch), 1.90 cm (.75 inch), and 2.54 cm (1 inch) (Figure 8). Results were then platted as time versus temperature.

Fig. 8 Top view of Sample Plate w/Thermo Couples

Cutting Parameters

The primary parameters varied during the cutting tests were as follows.

1. Laser Power (5 Kw to 22 Kw) .

2. Carriage Speed .21 cps (5 ipm) to 2.96 cps (70 ipm).

3. Gas composition (O_2. Air, N_2).

4. Gas pressure .69 MPa (100 psi) to 4.83 MPa (700 psi).

5. Nozzle orientation.

The parameter setting was first accomplished on uncoated steel plate of 1.90 cm (.75 inch), 3.17 cm (1.25 inches) and 5.40 cm (2.12 inches) thicknesses prior to cutting the plates with coatings. Numerous short cuts and partial cuts were made to establish which parameters were predominant in controlling cutting speed and penetration, especially in the thicker plate 3.17 cm (1.25 inches) & 5.40 cm (2.125 inches).

RESULTS OF TEST PROGRAM

Uncoated 1.90 cm (.75 inch) Thick HY-80 Plate

Laser cuts were performed with air, O_2 and N_2 as assist gases and 2.76 MPa (400 psig) and 4.14 MPa (600 psig) pressure. The O_2 resulted in the highest cutting speed (Figure 9) at a tradeoff of having the highest surface temperature profile. (See Figure 10 for air and Figure 11 for O_2).

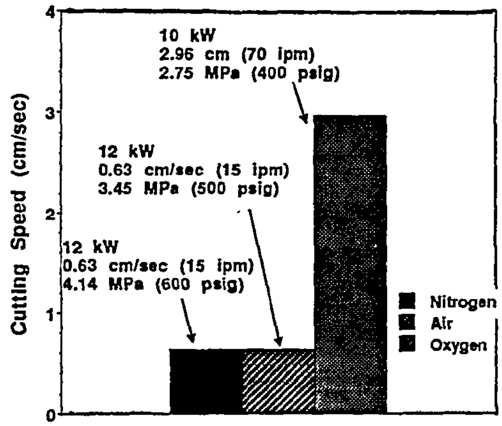

Fig 9. Cutting Gas Composition

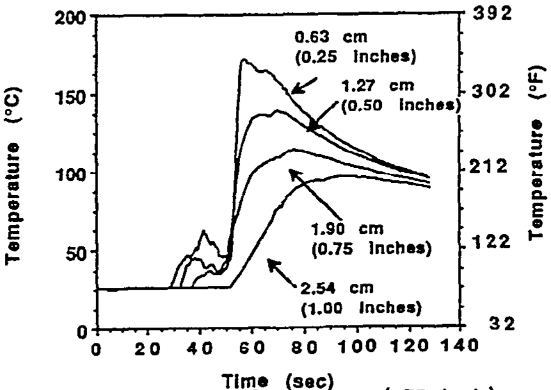

Fig. 10 Thermal Profile 1.90 cm (.75 inch) Plate. Cutting Parameters were 12Kw, 4.14 MPa (600 psig) air

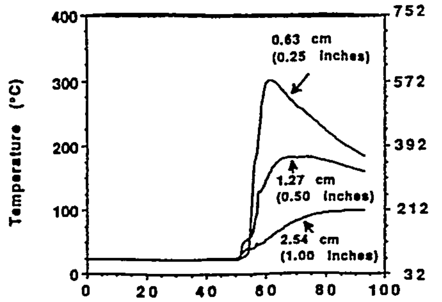

Fig. 11 Thermal Profile 1.90 (.75 inch) Plate. Cutting Parameters were 10Kw, 2.76 MPa, (400 psig), O_2

The higher temperature utilizing O_2 as an assist gas is directly related to an exothermic reaction that occurs between the o_2 and the steel. This reaction adds additional heat to the process as witnessed by additional puddling occurring on the cut surface. Since air is 24% oxygen, the same exothermic phenomenon also occurs using air, but not as extensive. When N_2 was used as an assist gas, the striations across the cut surface were more uniform due to the lack of oxidation. Figures 12A, 12B, 13A, 13B, 14A and 14B illustrate the differences in cutting among the assist gases. Also, acid etching of the cross sections of the cut surface revealed greater width for the O_2 HAZ Zone which explains the higher thermal profile for o_2. The slag deposits shown (Figures 12A, 12B, 13A, 13B, 14A & 14B) on the bottom of all three cuts were easily removed from the N_2 sample by tapping lightly with a hammer. The slag removal became increasingly more difficult with the air and O_2 samples. The kerf for the O_2 cut was .63 cm (.250 inch) as opposed to .76 mm (.030 inch) for N_2. The temperature advantage of utilizing N_2 as an assist gas was explored further when cutting coated materials.

Fig. 12_A_Laser Cut Curface (Air)

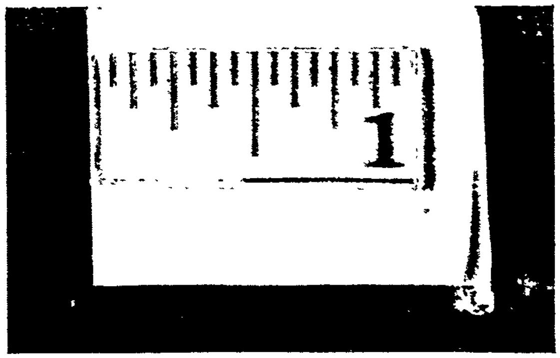

Fig. 12B Laser Cut Cross Section (Air)

Fig. 13A Laser Cut Surface (o_2)

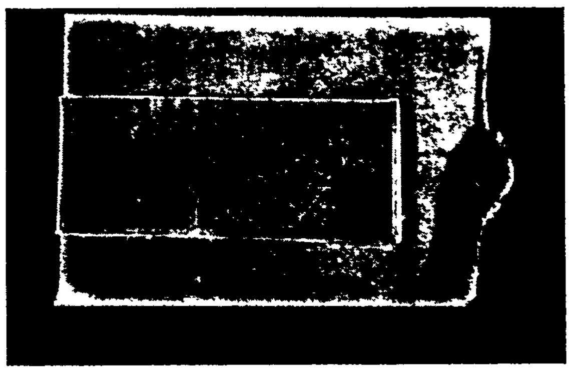

Fig. 13B Laser Cut Cross Section (o_2)

Fig_. 14A Laser Cut Surface (N_2)

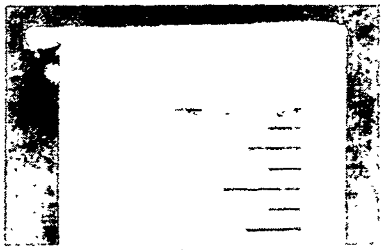

Fig. 14B Laser Cut Cross Section

Uncoated 5.40 cm (2.12 inches) Thick HY-80 Steel Plate.

Successful cuts of this heavy material were achieved at 21 cps (5 lprn) utilizing 4.14 MPa (600 psig) air as the assist gas (Figure 15). Thermocouple data was collected for this sample and plotted (Figure 16).

Fig.15 5.40cm(2.12in)thick, .76mm (.030in) kerf

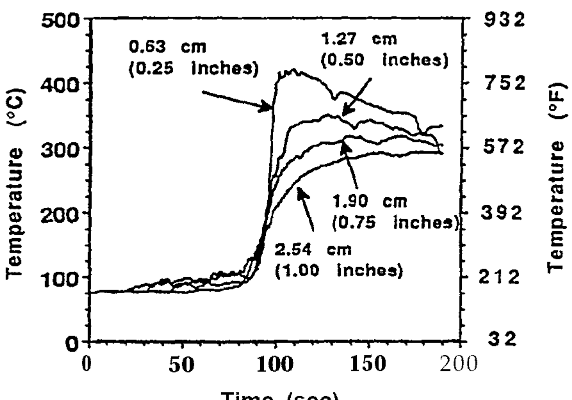

Fig. 16 Thermal Profile 5.40 cm (2.125 inch) Plate. Cutting Parameters were 15kw, 4.14 MPa (600 psig), air, .21 cps (5 ipm).

Coated .95 cm (.375 inch) Thick HTS Steel Plate With 1.71 cm (.675 inch) Rubber Coating on Bottomside.

Successful cuts were achieved with both air and N_2 used as cutting gases with the same power (12 Kw) and speed 1.69 cps (40 ipm). The observable difference in the cuts was the surface of the rubber coating. With air, a more oxidizing gas, the surface of the laser cut was rough, while for the N_2 the surface was smooth (Figures 17 & 18).

Higher cutting speeds were unsuccessfully attempted with both cutting gases. Smoke was generated With the use of N_2 and air.

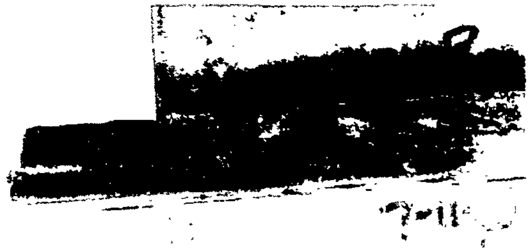

Fig. 17 Cut Surface Rubber & Steel)(Air)

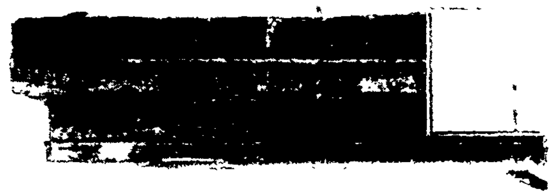

Fig. 18 Cut Surface Rubber & Steel (N_2)

Coated .95 cm (.375 inch) Thick HTS Steel Plate With Rubber Coatings On Both Sides.

The laser cuts were attempted using O_2, N_2, and air separately as the laser cutting gases. Various parameter settings were used but no successful complete cuts through all materials were made (Figure 19). The inclined nozzle design could be either aimed at the rubber surface where the laser beam was focused or at the steel surface where the laser beam was focused. The only test result was the cutting of the top rubber coating only at 10 Kw, 2.40 MPa (350 psi) air and 2.96 cps (70 ipm). No attempt was made to laser cut the exposed steel plate because of the nozzle configuration. Also, heavy smoke and flames were generated during cutting the rubber utilizing O_2. while only smoke was generated utilizing N_2 and air (less smoke with N_2). It was at this point in the test program that the need for a coaxial gas nozzle was realized. A coaxial design would be pursued for future cutting of layered materials.

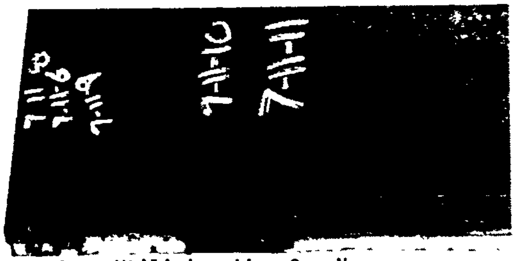

Fig. 19 Cuts Utilizing Air, O_2, N_2

Coated 2.86 cm (1.25 inches) Thick HY-80 Steel Plate With Foam Insulation on Backside.

Laser cuts through the combination of 1 1/4 HY-80 plate with foam insulation were accomplished utilizing O_2, air and N_2 as assist gases.

1. When O_2 was used as the assist gas at 3.45 MPa (500 psig and laser power at 20 Kw, the steel and insulation combination was cut at 1.69 cps (40 ipm). The typical exothermic reaction occurred with the steel cut surface. The backside insulation was ignited by the dross as accelerated by the

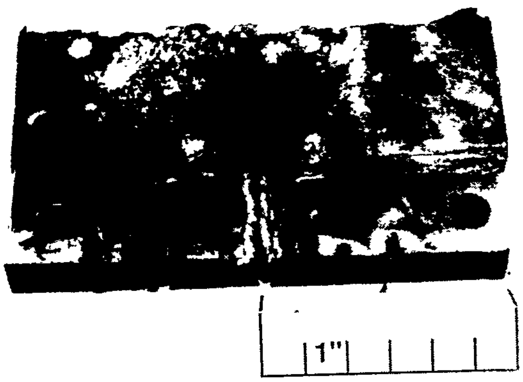

Fig. 20 Bottom View of Cut & Insulation (O_2)

pure O_2. The insulation burned for a 6.35 cm (2.50 inches) width centered on the laser cut line (see Figure 20, bottom view). The kerf width was approximately .63 cm (.250 inch). Backside ignition of materials would be unacceptable in a field application and would require insulation removal prior to laser cutting.

2. When air (24% O_2) was used as assist gas at 4.83 MPa (700 psig) and the laser power at 22 Kw, the combination of steel plate and insulation was cut at .42 cps (20 ipm). The backside insulation burned but not as severely as with pure O_2 assist gas. The backside insulation charred similar to that shown in Figure 21A,B. The ignition of insulation would also require removal prior to laser cutting.

Fig. 21A Bottom View of Cut & Insulations (Air)

Fig. 21B Top View (Typical) of Start of Cut. Note Width of Cut in Relation to Coin (Quarter). Also shown is Hypo Tube Gas Nozzle.

3. When N_2 was used as assist gas at 4.83 MPa

(700 psig) and laser power at 22 Kw the plate and insulation combination was cut at .42 c p s (10 ipm. There was no backside ignition and the insulation was vaporized (not burned) for a width of 3.81 cm (1.5 inch) centered on the laser cut. The cut was very smooth and the paint on the nearside of the laser cut was affected for a width of only .32 cm (.125 inch) (see Figures 22A & 22B).

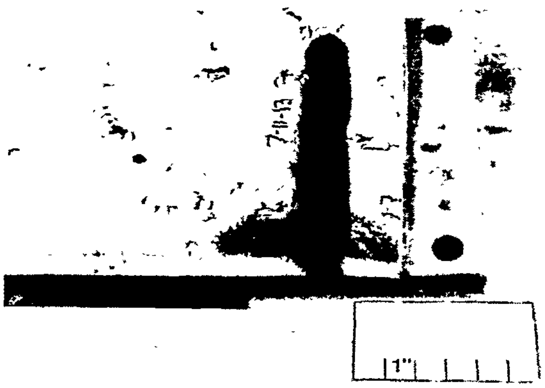

Fig. 22A Bottom View of Cut & Insulation (N_2)

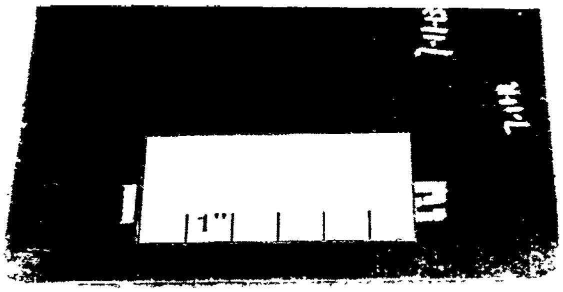

Fig. 22B Top View of Cut & Burned Paint

This cut was the most desirable from a field application standpoint as backside insulation would not have to be removed in way of the cut as would be required in conventional flame cutting techniques. Not having to remove backside interferences and insulation can be a great cost savings, especially when considering piping, wireways and equipment that must be removed in order to obtain access to the backside area. Laser cutting utilizing N_2 as assist gas has even further application and needs more testing to obtain environmental data on cutting steel plates with PCB contaminated material on the opposite side of the cut. A comparison of the cutting speeds of all three assist gases is shown in Figure 23.

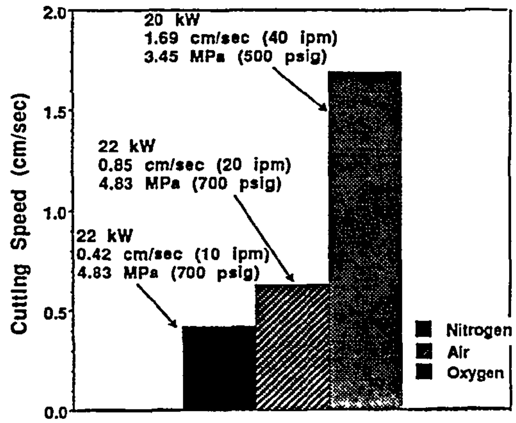

Fig. 23 Cutting Gas Composition

<u>Coated HY-80 Steel Plate 5.08 cm (2 inches) Thick With Foam Insulation On Backside.</u>

Successful laser cuts were made from the steel side through the combination of steel and insulation. Air was used as the **assist gas at 4.83 cm (700 psig)** and laser power at 22 Kw. The cutting speed obtained was .34 cps (8 ipm). Some opposite side combustion did occur of the insulation (see Figure 24, bottom view). Also, examination of the striations on the cut surface of Figure 24 shows the molten metal started in a vertical direction but changed direction due to the reduction of the gas flow momentum with increased depth of the cut. This indicates that more gas throughput is needed with the thicker materials. This condition also existed for the uncoated 5.40 cm (2 inches) thick steel plate.

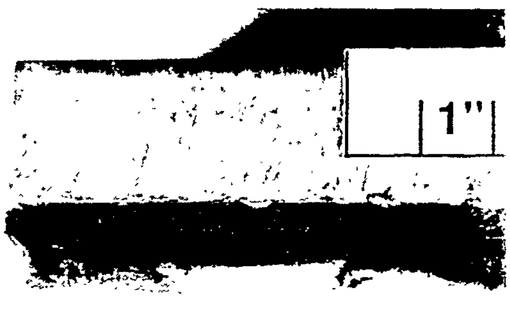

Fig. 24 Cut View of Striations & Insulation

Shielded 400 Ampere Power Cable, 6.35 cm (2.50 inches) In Diameter, Reinforced Wire Braiding And Three Internal Copper Cables 1.90 cm (.75 Inches) In Diameter.

A single pass of the laser beam at 20 Kw power level .85 cps (20 ipm), and O_2 at 1.38 MPa (200 psig) produced a cut through approximately 3/5 of the cable (see Figure 25). This cable is usually cut with a mechanical saw with great effort. The CO_2 laser illustrates that with some development work, this could be a very practical application.

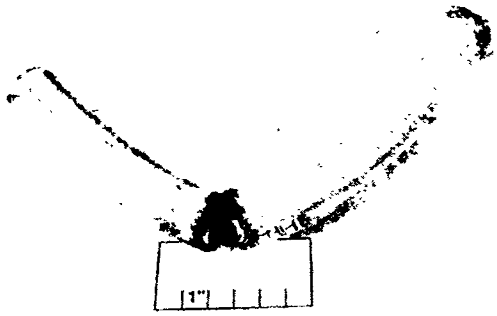

Fig. 25 Laser Cut 400 Ampere Power Cable

5.08 cm (2 inches) Diameter Copper Nickel (CUNI) Pipe With 5.08 cm (2 inches) Of Asbestos Insulation All Around (see Figure 7).

A single pass of the laser beam at 10 Kw power level, .63 cps (15 ipm) and O_2 at .69 MPa (100 psig) produced a 2.54 cm (1 inch) deep cut into the asbestos. The laser beam melted and cauterized the asbestos into a black silicone glass structure. (Figure 26). Environmental samples taken during the cutting operation indicated no airborne fibers were generated during the cutting. This application of laser cutting has far reaching potential and cost savings for adaptation to a shipboard or commercial system to cut asbestos covered piping with little or no hazard to the environment or workers and little protective clothing required to perform the work.

Fig. 26 Laser Cut Into Asbestos Insulation

CONCLUSION

The cutting tests performed (sec. Table 1) demonstrated all materials provided could be cut The use of an oxidizing gas such as O_2 or air (24% O_2) increases cutting speed but also significantly increases temperature adjacent to the cut. On coated materials , O_2 as air assist gas causes ignition of the backside coating, however, N_2 as an inert assist gas neutralizes the combustion effect. The type and orientation of the nozzle is critical for successful cutting. A coaxial nozzle would be much more effective in cutting layered materials and thick steel sections (greater than 5.08 cm (2 inches)). Assist gas pressure also has a great effect on cutting speed. As our 'K' size cylinders lost maximum pressure due to volume usage, cutting speeds were reduced. Connecting several cylinders in parallel would help minimize this pressure loss. Aiming the gas nozzle at a laser focus spot . 13 cm (.050 inch) on the surface of the material to be cut was also difficult. Again, a coaxial design would solve the aiming problems plus shield the laser beam from organic smoke which decouples the beam. All environmental data taken was within allowable specifications. The asbestos cutting was a pleasant surprise as was with the heavy power cable. The 25 Kw co_2 laser certainly demonstrated sufficient power to cut all thicknesses provided especially when the proper gas pressure and gas momentum was achieved.

Future Applications

The use of N_2 assist gas at 4.83 MPa (700 psig) with the 25 Kw CO_2 laser proved a winning combination With the design and manufacture of a beam delivery system. this system could be used to cut heavy sections In shipyards and other heavy industrial activities. Using this combination. preliminary tests indicate Insulation may be left in place realrzing a large cost savings as opposed in having to remove interferences plus insulation. With the high temperature of the laser beam (greater than 5000 degrees Fahrenheit) and high power density 10^{10} watts/cm^2 (10^9watts/in^2). the ability of the laser to incinerate/vaporize hazardous materials such as PCB's certainly warrants further testing. If the backside material had to be removed, with the low temperature .63 cm (1/4 inch) away from the centerline of the cut and steep thermal gradient. the amount of material required to be removed is far less (could be less than 2.54 cm (1 inch) than conventional flame cutting in a PCB environment. A fire watch would still be recommended for laser cutting.

The asbestos cutting has potential to be developed into a delivery system (perhaps a Yttrium Aluminum Garnet (YAG) Laser/Fiber Optics combination) that could be used to cut asbestos coated piping with little effect on the environment and worker, again another potential large cost savings over conventional methods.

Materials (Thickness; Condition)	Power (kW)	Speed cm/sec (ipm)	Gas Comp.	Gas Pressure MPa (psig)
1.9-5.4 cm (0.75-2.13 inches); Bare & Coated Plates	10-22 kW	0.64-2.96 cm/sec (15-70 ipm)	Nitrogen Air Oxygen	2.8-4.8 MPa (400-700 psig)

Table I. Summary of Laser Test Parameters Performed